DESIGNING CLIMATE AND WATER POLICIES FOR AGRICULTURE

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DOCTORAL DISSERTATION

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ABSTRACT

This thesis studies the design of socially optimal policies for climate mitigation and water protection for two agricultural production lines: crop and dairy production. It provides analytical insights into optimal management, both in the absence and presence of nutrient runoff and greenhouse gas emissions, and develops policies to incentivize private production when externalities to water and atmosphere exist. Special attention is devoted to the coeffects of agricultural water protection measures on climate mitigation and of climate mitigation measures on water protection and their implications for marginal abatement costs and optimal policies. The thesis studies crop rotations with legumes and dairy production in detail. It additionally derives cost functions for reducing emissions by combining individual measures, such as fertilization, buffer strips, catch crops, tillage methods, afforestation and green fallow.

In general, Pigouvian taxes on greenhouse gas emissions or on diffuse nutrient loading as first-best policies are not possible due to problems in measuring nonpoint source loading. Therefore, second-best policies, such as uniform taxes levied on animal numbers or fertilization or subsidies based on buffer strip width or transporting manure, are developed and applied numerically. Based on the findings, in comparison to the first-best policies, the second-best policies are relatively effective in producing the desired policy goals. Study I of the thesis shows how legumes in crop rotations outperform cereal monocultures economically and environmentally in many cases, provided there is adequate demand for legumes, and develops differentiated nitrogen tax and buffer strip subsidies based on the cultivated crop. Study II focuses on the use of nitrogen, land use, dairy cow diet and climate emissions within dairy production. This study demonstrates the overall spatial pattern of manure application and illustrates the main measures to reduce greenhouse gas emissions and nutrient runoff. Uniform nutrient taxes are found functional, although spatially differentiated taxes produce higher welfare. Study III highlights the importance of accounting for multiple pollutants and their coeffects when designing environmental policies and calculating marginal abatement costs. In the case of cobenefits, the optimal tax on the focus pollutant is relatively higher, increasing abatement and the supply of cobenefits.

Keywords: greenhouse gas emissions, nutrient runoff, dairy management, manure, crop rotation, legumes, marginal abatement costs, economic instruments

TIIVISTELMÄ

Väitöskirja tarkastelee yhteiskunnallisesti optimaalisen ilmasto- ja vesistöpolitiikan muotoilua ohjaamaan kasvinviljelyä ja maidontuotantoa kestävämmäksi. Maatilan optimaalinen hallinta ratkaistaan analyyttisesti sekä yksityisen viljelijän että yhteiskunnan näkökulmasta, kun yhteiskunta ottaa huomioon tuotannon aiheuttaman ravinnehuuhtouman ja kasvihuonekaasupäästöt. Väitöskirja kehittää ohjauskeinoja, joilla viljelijöitä ohjataan huomioimaan ilmaan ja vesistöihin kohdistuvat maatalouden ulkoisvaikutukset päätöksissään. Lisäksi tarkastellaan maatalouden vesistötoimenpiteiden ilmastolle aiheuttamia sivuvaikutuksia ja ilmastotoimenpiteiden vesistöille aiheuttamia sivuvaikutuksia, sekä sitä, miten näiden sivuvaikutusten huomiointi muuttaa rajapuhdistuskustannuksia ja optimaalisia ohjauskeinoja. Väitöskirja tutkii yksityiskohtaisemmin palkokasveja sisältäviä viljelykiertoja sekä maidontuotantoa. Rajapuhdistuskustannuksia määritettäessä yksittäisiä toimenpiteitä, kuten lannoitus, suojakaistat, kerääjäkasvit ja maanmuokkausmenetelmä, yhdistetään.

Hajakuormituksen mittausongelmien vuoksi Pigou-malliset verot kasvihuonekaasupäästöille tai ravinnehuuhtoumalle eivät ole mahdollisia. Siksi väitöskirjassa tarkastellaan second-best-ohjauskeinoja, kuten eläinten tai lannoituksen määrään perustuvaa veroa. Tulosten perusteella second-best-ohjauskeinot tuottavat melko lähellä first-best-ohjauskeinoja olevan lopputuloksen. Artikkelin I perusteella palkokasveja sisältävät viljelykierrot ovat usein talouden ja ympäristön kannalta viljojen monokulttuureja parempia, mikäli palkokasvien kysyntä on riittävä. Artikkelissa kehitetään viljelykasvin mukaan vaihtuva typpivero sekä suojakaistatuki. Artikkeli II keskittyy typen ja maankäyttöön, eläinten dieettiin ja ilmastopäästöihin maidontuotannossa. Artikkeli esittää etäisyyden suhteen optimaalisen lannan levityksen rakenteen ja pääasialliset toimenpiteet ravinnehuuhtouman ja kasvihuonekaasupäästöjen vähentämiseksi. Vakioiset ravinneverot todetaan toimiviksi, vaikka etäisyyden mukaan vaihtuva vero tuottaisi korkeamman hyvinvoinnin. Artikkeli III korostaa useiden päästölähteiden ja näiden sivuvaikutusten yhtäaikaisen huomioinnin tärkeyttä ympäristöpolitiikan suunnittelussa ja rajapuhdistuskustannusten määrityksessä. Jos politiikka tuottaa sivuhyötyjä, politiikan kohteena olevan päästön optimaalinen vero on korkeampi, jolloin sivuhyötyjen tarjonta lisääntyy.

Avainsanat: kasvihuonekaasupäästöt, ravinnehuuhtouma, maidontuotanto, lanta, viljelykierto, palkokasvi, rajapuhdistuskustannus, taloudelliset ohjauskeinot

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LIST OF ORIGINAL PUBLICATIONS

This thesis is based on the following studies:

I. Lötjönen, S. and Ollikainen, M. 2017. Does Crop Rotation with Legumes Provide an Efficient Means to Reduce Nutrient Loads and GHG Emissions? *Review of Agricultural, Food and Environmental Studies* 98 (4): 283−312. https://doi.org/10.1007/s41130-018-0063-z

II. Lötjönen, S., Temmes, E. & Ollikainen, M. 2020. Dairy farm management when nutrient runoff and climate emissions count. *American Journal of Agricultural Economics* 102 (3): 960−981. https://doi.org/10.1002/ajae.12003

III. Lötjönen, S. and Ollikainen, M. 2019. Multiple pollutant cost-efficiency: coherent water and climate policy for agriculture. *Ambio* 48 (11): 1304−1313. https://doi.org/10.1007/s13280-019-01257-z

AUTHOR'S CONTRIBUTION

SL=Sanna Lötjönen, MO=Markku Ollikainen, ET=Esa Temmes

Study I SL is the corresponding author. MO provided the research idea. SL performed the calculations. SL and MO wrote the article.

Study II SL is the corresponding author. MO and ET performed the initial version of the code, and SL extended the code with more details and GHG emissions to its final version. SL performed all calculations. MO and ET wrote the first draft of the article without climate issues, and SL and MO wrote the final version of the article.

Study III SL is the corresponding author. MO and SL developed the research idea. SL performed the calculations. SL and MO wrote the article.

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1. INTRODUCTION

1.1. Background and motivation

Climate change and biodiversity loss are two of the major challenges the world is currently facing (IPCC 2018, CBD 2014), followed by problems relating to the quality and quantity of water. The urgency of climate change mitigation has also risen on political agendas. To achieve the greenhouse gas (GHG) mitigation goals set in the Paris Agreement in 2015 and to limit global warming to a maximum of 1.5°C above preindustrial levels (UNFCC 2015), all sectors and countries are required to take action. Globally, in 2010, agriculture, forestry and other land use (AFOLU) contributed to direct GHG emissions by approximately 24% (IPCC 2014). Of the agricultural non-carbon dioxide emissions, approximately 80% originates from livestock, and of those, the largest part stems from ruminants (Havlik et al. 2014). In Finland, agriculture accounts for approximately 12% of the country's total GHG emissions (Statistics Finland 2017). In the EU Effort Sharing Regulation, emissions not covered by the EU emissions trading scheme or the land-use, land-use change and forestry (LULUCF) sector, such as transportation and agriculture, must be reduced by 30% by 2030 compared to the levels in 2005 (EC 2019a). For Finland, the reduction target is 39%. LULUCF will be included in the EU climate policy starting in 2021 (EC 2019b). The EU regulation includes a no-debit rule, implying that the LULUCF sector should not be a net emitter. The policy will most likely induce national climate policies for the land-use sector and create more pressure than before to mitigate GHG emissions from agricultural soils and production.

Nutrient loading worsens water quality leading to eutrophication. Eutrophication is becoming more severe due to climate change as waters become warmer and runoff is predicted to increase (IPCC 2019). For water quality, the EU Water Framework Directive (2000/60/EC) requires achieving good ecological status of surface waters by 2027, and the HELCOM Baltic Sea Action Plan, adopted in 2007, aims to achieve good ecological status of the sea by 2021 (HELCOM 2007). In Europe, the Baltic Sea is facing large-scale algal blooms resulting from excess nitrogen (N) and phosphorus (P) loadings to the sea that are reinforced by the release of phosphorus from anoxic sea bottoms (the internal loading). Agriculture is the largest source of nutrients, accounting for between 60% and 90% of the anthropogenic diffuse nutrient loads in the Baltic Sea (HELCOM 2011).

How to response to these challenges of climate change and eutrophication in agriculture provides an interesting and necessary line of research. It is important to understand the best measures to reduce nutrient loading and GHG emissions, and how privately and socially optimal management differ. Another factor are the simultaneous impacts of measures targeting climate and water on GHGs and nutrient runoff, and how these impacts should be accounted for in the policy design. Agriculture as a sector is not homogenous but consist of several production lines with unique features. The clearest division is between crop production and animal production. The question arises whether these two production lines require different approaches and whether similar solutions function for both. The underlying question is what the best policy instruments are to reduce nutrient loading and GHG emissions, to account for the simultaneous impacts of abatement measures, and to account for the specific characteristics of different production lines. These issues constitute the broad thematic questions of this paper and they will be discussed at the farm level.

This thesis focuses on two agricultural production lines: crop and dairy production. These two production lines differ from one another in terms of sources of emissions and the possibilities to abate them. Therefore, their examination also requires a different kind of framework, and the production lines are discussed separately. Animal husbandry in mixed animal-crop farms creates a link between the two production lines and between nutrient loading and GHG emissions through manure and the production of feed. Manure creates a specific problem for animal husbandry, as it provides nutrients for cultivation but is simultaneously a free by-product, possibly causing pollution.

The main GHGs emitted from agricultural activities are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). According to the Intergovernmental Panel on Climate Change (IPCC) Guidelines for national GHG inventories, accounting for GHG emissions from agriculture in EU policy is divided into three sectors: agriculture, LULUCF, and energy (IPCC 2006). This thesis focuses on emissions from the agricultural sector (N_2O and CH_4) and from LULUCF (CO_2; soil emissions). Crop production produces most of the N_2O and CO_2 emissions; N_2O stems mainly from soils and CO_2 from the production of mineral fertilizers with the conventional, energy intensive Haber-Bosch method (Postgate 1998). The main GHG from animal husbandry is CH_4 from ruminant enteric fermentation. Different GHGs are comparable with the 100-year global warming potential (GWP_{100}), and they are thus converted to CO_2 equivalents (CO_2e).

N and P loads are the main sources of nutrient runoff. Nutrient runoff originates from fields under cultivation. In animal husbandry, manure that is excreted on pastures and spread on cultivated fields causes nutrient loading. Nutrient runoff is commonly described with one metric, nitrogen equivalents (Ne). For the Baltic Sea case, P is converted to Ne with the Redfield ratio, which describes the usability of N and P to blue algae (Kiirikki et al. 2003). This rate differs among waterways. For example, in Finnish lakes, P is the limiting factor for algal blooms, and in the Baltic Sea, the limiting factor is most often N. Recently, the runoff of dissolved organic carbon has gained increasing attention (see IPCC 2019). However, scientific knowledge of its role in eutrophication and GHG emissions is not adequate to include it in the present study.

Due to the diffuse nature of agricultural loading, nutrient runoff is difficult to measure and reduce compared to point sources in many other sectors (Shortle and Dunn 1986; Segerson 1988). Agricultural production with current techniques also unavoidably causes some amount of loading into waterways and the atmosphere. Loadings from agriculture vary, especially due to stochastic weather, which the farmer is not able to control and which makes the effect of abatement measures on nutrient runoff and on ambient concentration levels uncertain (Segerson 1988). Due to stochastic weather and site-specific conditions, such as soil type, the effect of abatement measures on loading is also site-specific. In most cases, multiple farms contribute to the same water system, in addition to natural loading, complicating the monitoring of nutrient loading from a single farm (Segerson 1988). As each site is different, the way how nutrients flow through soil to waterways varies creating a unique influence from each individual field plot on eutrophication. Considering this becomes relevant when multiple farms are included in the analysis. Nonpoint nutrient runoff can ultimately be described as a probability density function, where the expected value describes the average runoff, and the tails depict the minimum and maximum runoff levels with prevailing management practices. Changing management practices alters the probability distribution, i.e., not only does the expected runoff change but also the likelihood of lower and higher realizations. In this thesis, the focus is on the expected nutrient runoff and, therefore, policies are developed to target the expectation only.

The characteristics of nonpoint source nutrient loading are well known in the economic literature. As actual runoff might be unobservable or extremely expensive to monitor, policies based on actual loading (such as Pigouvian taxes) are not possible (Griffin and Bromley 1982; Shortle and Horan 2001). Instead, policy mechanisms can be levied on inputs affecting runoff (Griffin and Bromley 1982), such as fertilization (Shortle and Horan 2001). It is crucial to use nonpoint runoff functions, which determine the connection between inputs or activities and the estimated runoff (Griffin and Bromley 1982; Shortle and Dunn 1986). In general, four policy types have been identified for nonpoint pollution: policy can be based on incentives or standards on estimated runoff or on management practices (Griffin and Bromley 1982; Shortle and Dunn 1986). Additionally, the ambient concentration of nutrients is suggested as the compliance base to ensure actual reductions in runoff (Segerson 1988; Shortle and Horan 2001). In the long run, the four policy types differ in terms of sharing the cost burden between parties and thus affect the entry and exit of farms (Griffin and Bromley 1982). In addition to the policy types presented above, voluntary environmental agreements are possible (see Wu and Babcock 1999), and they are currently widely used. For example, the common agricultural policy in the EU requires all member countries to create voluntary environmental schemes and agreements for their farmers (EC 2019c).

Generally, the basic production unit considered is a homogenous, representative land parcel. Nutrient loads depend, however, on the fertilizer intensities of the cultivated crop and land allocation between the crops, as well as on entry/exit conditions of arable land. A framework that facilitates the endogenous analysis of these features is the Ricardian approach, where the unit is also a homogenous parcel of land but productivity between parcels varies (Lichtenberg 1989). Lichtenberg (1989) and Lankoski and Ollikainen (2003) generalized the examination of nonpoint source loading to heterogeneous soils. Although the general features of nonpoint loading have been substantially studied, there is still a lack of literature on the optimal choices and policies regarding dairy production and legumes.

As opposed to that on nutrient runoff, less economic research on climate and agriculture has been conducted. Simulation models are plentiful (see Schils et al. 2007 for animal husbandry), but theoretical treatments are lacking. Mitigation policies for agricultural emissions have been studied by for example Lankoski et al. (2020), Ervola et al. (2018), De Cara et al. (2015) and Bakam et al. (2012). Agricultural GHG emissions can be considered point sources, but measurement difficulties similar to those for diffuse loading persist. Additionally, vast uncertainties occur in natural sciences, such as the carbon sequestration of agricultural soils under different management practices and for different crops.

An additional feature relates to the possible coeffects of climate mitigation and water protection measures in agriculture. Measures aimed at reducing GHG emissions can have a positive or negative effect on nutrient runoff, and vice versa. Coeffects, be they positive or negative, need to be accounted for as they may alter the optimal abatement rate and affect marginal abatement costs (see Ollikainen et al. 2019; Eory et al. 2018). If these impacts are neglected, then policies designed to prevent one type of pollution may actually have an adverse impact on the flow of another pollutant.

1.2. Objectives of the thesis

This thesis examines the optimal climate and water policies for agriculture at farm level with the special focus on creating incentives for farmers to take measures and actions to reduce the environmental impacts of agricultural production. While the importance of climate mitigation and water protection in agriculture is widely acknowledged, economic literature lacks the simultaneous and analytical accounting of nutrient loading and GHG emissions in many measures. The general research question is **how to design socially optimal policies for climate mitigation and water protection in crop and dairy production**. The thesis provides analytical insights into optimal management and choices both from the perspective of a private farmer and of society. Based on the differences between privately and socially optimal management, policies are developed to guide private production when externalities to water and atmosphere exist. Policy instruments considered include taxes and subsidies based on estimated emissions, production factors, animals and other units, and restrictions such as on herd size and fertilization. The thesis also studies the coeffects of water protection measures on climate mitigation and of climate mitigation measures on water protection and their implications for optimal policies.

The more detailed topics covered in the thesis are crop rotations with legumes (Study I), dairy production (Study II), and marginal abatement cost calculations (Study III). For legumes in crop rotation, analytical economic studies are nearly absent, while a few studies focus empirically on economic aspects (see Reckling et al. 2016a; 2016b). Dairy production has mostly been studied focusing on the use of P and on the private optimum (Schnitkey and Miranda 1993; Innes 2000). This thesis focuses on the use of N, including both pollutants (nutrients and GHGs), and determines the optimum for both a private farmer and society. Marginal costs for simultaneously reducing nutrient loads and GHG emissions in agriculture have not been studied in the Baltic Sea region, and policy implications of accounting for multiple pollutants are inadequately analyzed (see Ambec and Coria 2013; Ervola et al. 2018). This thesis provides new analytical insights on each of these topics. Numerical farm level simulations drawing on data from Finnish boreal agriculture supplement each point and provide further insights. Table 1 summarizes the key elements in each of the studies.

Table 1. Summary of the key contents of the studies

Study	Field	Measures	Pollutant	Approach
I	Crop	Crop rotation, legumes	GHG, nutrient	Profit/welfare maximization
II	Dairy + crop	Herd size, diet, manure management, fertilization, land allocation	GHG, nutrient	Profit/welfare maximization
III	Dairy + crop	Herd size, diet, manure management, fertilization, land allocation, crop rotation, legumes, tillage method, catch crop, buffer strip, afforestation, green fallow	GHG, nutrient	Derivation of cost functions for agriculture

Specifically, the separate research questions for Studies I-III are as follows: Study I considers whether crop rotations with legumes provide better economic and environmental outcomes compared to cereal monocultures. It focuses on how cereal monocultures perform in comparison to crop rotations with legumes in terms of profitability and in reducing GHG emissions and nutrient runoff. It also defines both private and social optima and solves optimal policies to induce socially optimal choices. Study II analyzes how the optimal management of a dairy farm changes when nutrient runoff and greenhouse gas emissions are included in the analysis as damages. It studies how privately and socially optimal management decisions differ from one another, what kind of policy instruments would be optimal to guide private management decisions to the social optimum, and which measures are taken first to reduce GHG emissions and nutrient runoff. Study III examines how accounting for multiple pollutants affects marginal abatement costs and optimal water and climate policies for agriculture.

2. WATER PROTECTION AND CLIMATE MITIGATION MEASURES IN LIGHT OF THE LITERATURE

Given the need and urgency described above, what are the possible measures to reduce GHG emissions and nutrient loading from agriculture? The measures differ between the two production lines (crop and dairy production); therefore, they are discussed separately in the following sections. This chapter briefly describes the measures considered and their effects on GHG emissions and nutrient runoff within boreal Finnish agriculture on clay soil and provides a brief review of economic studies.

2.1. Agriculture and climate mitigation measures: synthesis of the main findings

In crop production, GHG emissions can be reduced, such as by introducing buffer strips, using less mineral fertilizers or cultivating grasses and legumes instead of cereals. Measures in dairy production include reducing herd size and altering manure management practices and diets. Table 2 condenses the effects of changing the extent of selected measures on GHG emissions: whether emissions increase (+), decrease (-) or are not affected (0) due to the change in the measure.

Table 2. Measures to reduce GHG emissions, affected GHGs and the direction of change[1]

Dairy production	**CO_2**	**N_2O**	**CH_4**
Reduced herd size	+/-	+/-	-
Decreasing concentrate intake in the diet	0	0	+/-
Covering manure storage	0	+	-
Manure injection spreading (compared to broadcast)	0	+?	0
Crop production			
Reduced fertilization	-	-	0
Widened buffer strips	-	0	0
No-till (compared to conventional tillage)	+	+	+
Catch crops	-	-	0
Legumes in crop rotations (compared to cereal monoculture)	-	-	0
Land allocation (grasses vs. cereals)	-	+	-
Afforestation (compared to cereal monoculture)	-	+	-
Green fallow (compared to cereal monoculture)	-	+	-

Note: + = GHGs increased, - = GHGs decreased, 0 = GHGs are not affected by the measure, CO_2 = carbon dioxide, N_2O = nitrous oxide, and CH_4 = methane.
[1]Based on Study I; Study II; Ervola et al. (2012, 2018); Valkama et al. (2015); modified from Study III.

In dairy production, reducing herd size is the most effective measure to lower GHG emissions. This directly decreases CH_4 emissions from enteric fermentation, while the indirect reductions stem from feed production and manure management. What happens to land allocation and fertilization defines the direction of change in CO_2 and N_2O emissions. Diet can be altered by, for example, varying concentrate feed intake, which slightly affects enteric fermentation emissions. Whether lower concentrate intake increases or decreases CH_4 emissions depends on the initial concentrate feeding level (based on Study II). In comparison to not covering manure storage, covering manure storage increases N_2O emissions and decreases CH_4 emissions (based on Statistics Finland 2016; Grönroos 2014). The overall effect is a decrease in CO_2e emissions. Manure spreading technologies mainly affect nutrient runoff. The effect of manure injection spreading compared to broadcast spreading is somewhat unclear, but it might increase N_2O emissions (Webb et al. 2010; Duncan et al. 2017).

Reducing GHG emissions from dairy production has mainly been studied by various simulation models (for a list of models, see Schils et al. 2007). Mosnier et al. (2019) calculated the costs of GHG abatement measures in French dairy production by comparing the results of four bioeconomic simulation models while increasing a carbon tax on GHG emissions. They found that only a very high tax (100 €/tCO_2e) would result in up to a 15% decrease in GHG emissions without a substantial compromise in milk production or the abandonment of some input production.

In cultivation, reducing fertilization lowers CO_2 emissions from mineral fertilizer manufacturing and soil N_2O emissions related to fertilization. Buffer strips remove field area from cultivation, and they additionally sequester carbon due to the perennial grasses grown in the area (Lal 2004; Ervola et al. 2012). Conventional tillage compared to no-till technology reduces CO_2e emissions in clay soils in boreal agriculture (Ervola et al. 2012). Catch crops are cultivated with or between main crops mainly to reduce nutrient losses (Valkama et al. 2015), and they sequester carbon by increasing the carbon content in the soil (MacLeod et al. 2015). Fields can also be afforested or turned to green fallow to avoid cultivation-related emissions and sequester carbon in the soil and trees (Ervola et al. 2012; clay).

Crop rotations with legumes reduce GHG emissions compared to cereal monocultures as 1) legumes fix N biologically from the air, thus lowering the need for mineral fertilizers, both in the current and subsequent cultivation periods, and 2) emissions from soil are estimated to be lower for legumes than for cereal monocultures. The profitability of crop rotations with legumes tends to stay somewhat lower than that of monocultures, but crop rotations are often found to reduce GHG emissions (Reckling et al. 2016a; 2016b). The marginal costs of GHG mitigation using legumes are estimated to be between 19 and 43 €/tCO_2e (Dequiedt and Moran 2015). However, analytical economic studies on crop rotations with legumes are lacking.

For the entire French agricultural sector, Pellerin et al. (2017) calculated the GHG mitigation costs. They found that one-third of the total abatement potential, 32.3 tCO_2e/year assuming additivity, is achievable with negative costs, and another third with a cost less than 25 €/tCO_2e. Measures with negative costs include, among others, technical adjustments such as precision fertilization, adjustments to animal diets and increased legume share in pastures, and measures with moderate costs include, among others, reduced tillage and increased overall cultivation of legumes. MacLeod et al. (2015) found that measures related to fertilization, breeding and energy efficiency seem the most cost-effective. However, Pellerin et al. (2017) in addition to others (e.g., Lankoski et al. 2020; Eory et al. 2018) note that marginal abatement costs are highly dependent on local conditions, assumptions, included measures, and the technical implementation of calculations.

2.2. Agriculture and water protection measures: synthesis of the main findings

Agricultural nutrient runoff can be reduced in multiple ways. In crop production, measures include introducing buffer strips, using legumes in crop rotations, reducing fertilization, introducing catch crops, and altering tillage methods. Measures in dairy production consist of manure application and storage techniques. Table 3 condenses the effects of changing the extent of selected measures on nutrient runoff, i.e., whether runoff increases (+), decreases (-) or is not affected (0) due to the change in the measure.

Table 3. Measures to reduce nutrient runoff, affected nutrients and the direction of change[1]

Dairy production	**N**	**PP**	**DRP**
Reduced herd size	-	-	-
Manure injection spreading (compared to broadcast)	0	-	-
Crop production			
Reduced fertilization	-	-	-
Widened buffer strips	-	-	-
No-till (compared to conventional tillage)	-	-	+
Catch crops	-	0	0
Legumes in crop rotations (compared to cereal monoculture)	-	0	0
Land allocation (grasses vs. cereals)	-	-	+
Afforestation (compared to cereal monoculture)	-	-	-
Green fallow (compared to cereal monoculture)	-	-	-

Note: + = runoff increased, - = runoff decreased, 0 = runoff not affected by the measure, N = nitrogen, PP = particulate phosphorus, and DRP = dissolved reactive phosphorus.
[1]Based on Study I; Study II; Ervola et al. (2018); Valkama et al. (2015); Uusi-Kämppä and Heinonen-Tanski (2008); Lankoski et al. (2006); modified from Study III.

In dairy production, a reduction in herd size reduces manure excretion, which in turn reduces nutrient runoff related to manure management. Injecting manure into the soil instead of broadcast spreading reduces P runoff by approximately 80% (Uusi-Kämppä and Heinonen-Tanski 2008). The effect of spreading technology on N runoff is unclear (see Rotz 2004; Uusi-Kämppä 2010; Uusi-Kämppä and Mattila 2010).

For GHGs, simulation models exist that focus on dairy production and nutrient loading, such as those in Yap et al. (2004), Bosch et al. (2006) and Baerenklau et al. (2008). Simulation studies argue that measures related to cultivation should precede changes in feed composition to avoid losses in milk yield (Helin 2014), stress the tradeoffs if possible negative coeffects of a measure are not considered (Key and Kaplan 2007), and study the effects of constraining manure nutrient application on fields (Kaplan et al. 2004). Analytical economic studies focusing on dairy production and nutrients are relatively scarce, the most important ones including Schnitkey and Miranda (1993) and Innes (2000) that focus on the use of P.

In crop production, reducing fertilization directly lowers nutrient runoff. Buffer strips lower the land area for cultivation, thereby decreasing per-hectare runoff, and additionally, they catch some nutrients (Lankoski and Ollikainen 2003). The effect of the tillage method on nutrient loading varies among nutrients. Compared to conventional tillage, no-till causes lower nitrogen and particulate phosphorus loads but higher loads for dissolved phosphorus (Lankoski et al. 2006). Lankoski et al. (2006) found that in comparison to no-till, conventional tillage in cereal cultivation provided higher private profits and social welfare, while no-till was more profitable only for barley cultivation. Catch crops use the surplus nitrogen left in the soil after harvesting the main crop (Valkama et al. 2015). In comparison to cereal monocultures, legumes in crop rotations lower nutrient runoff (Recling et al. 2016b) in addition to GHG emissions, as biologically fixed nitrogen lowers the need for mineral fertilization and as the average runoff from legume cultivation is below the average nutrient runoff from cereals. By afforesting or green fallowing cultivated fields, nutrient loadings related to cultivation are avoided.

3. MODELS AND DATA

The three studies of this thesis use unconstrained and constrained optimization to maximize profits and welfare and derive cost functions (for a general description of the methods, see Simon and Blume 1994). Numerical simulations are performed with Excel (Microsoft, USA), Mathematica (Wolfram Research, Inc., USA), MATLAB (The MathWorks, Inc., USA) or/and @risk (Palisade, USA). The next subsections provide a brief overview of the models and the data used in the thesis.

3.1. Crop production model for crop rotation and legumes

The crop production model of Study I consists of a single crop rotation sequence within which leguminous crops are cultivated in rotation with cereals. Nitrogen response functions for crop yield (y_i, with i denoting the period within the rotation) are modified for legumes to account for biological N fixation as described in the following text. In the period of legume cultivation, the N response includes biologically fixed N, N_i, in addition to mineral fertilization, l_i (yielding $y_i(N_i + l_i)$). In the period after legume cultivation, the N response includes residual N (i.e., the biologically fixed N left in the field after harvest in the roots and harvest residues), n_i (yielding $y_i(n_i + l_i)$).

Private profits (1a) and social welfare (1b) from crop production under prevailing prices and costs are expressed as a function of the decision variables and are maximized as follows:

(1a) $$\max_{\{l_i,m\}} \sum_{i=1}^{I} (1+r)^{1-i} \pi_i^j(l_i, m),$$

(1b) $$\max_{\{l_i,m\}} \sum_{i=1}^{I} (1+r)^{1-i} (\pi_i^j(l_i, m) - d^c h_i^j(l_i, m) - d^w z_i^j(l_i, m)),$$

where i denotes time, i.e., the period in the rotation; I is the total number of periods in the rotation; and j denotes the crop cultivated in period i. Private profits from cultivation, π_i^j, include the residual effect of legumes, i.e., the yield increasing effect on the subsequent crop. d^c denotes the social marginal damage from GHG emissions, and d^w represents the social marginal damage from nutrient loading, while h_i^j and z_i^j are GHG emissions and nutrient loading, respectively, from the cultivation of crop j. All π_i^j, h_i^j and z_i^j are functions of the decision variables: fertilization for each period, l_i, and buffer strip width, m. Study I maximizes the discounted net present value, r denoting the real interest rate, in (1a) and (1b) for each rotation and monoculture, and chooses the one providing the highest profits or welfare.

From eqs. (1a) and (1b), the optimal policy instruments to equalize the private optimum with the social optimum are solved: a tax on nitrogen fertilization t_i (2a) and a buffer strip subsidy s (2b):

(2a) $$t_i = d^c \frac{\partial h_i^j}{\partial l_i} + d^w \frac{\partial z_i^j}{\partial l_i},$$

(2b) $$s = \sum_{i=1}^{I} (1+r)^{1-i} * [d^c \frac{\partial h_i^j}{\partial m} + d^w \frac{\partial z_i^j}{\partial m}].$$

The fertilizer tax on nitrogen fertilization (2a) consists of marginal climate damage multiplied by the marginal increase in climate emissions due to one unit of mineral fertilizer (constant value) and marginal water damage multiplied by the propensity for runoff (value varying between crops). If only climate damage is considered, then the fertilizer tax is uniform across crops. If only water damage or both climate and water damage are considered, then the tax is at a relatively higher level and differentiated between crops. The same applies for the buffer strip subsidy. For the subsidy (2b), note that the buffer strip affects nutrient runoff and GHG emissions via two channels: 1) the overall level of fertilization per land area decreases as a buffer strip reduces the area in cultivation, and 2) a buffer strip sequesters carbon and stops and fixes the released nutrients from fields per se. The marginal climate and water damage from buffer strips are thus negative; i.e., the carbon sequestration and reduced runoff provide climate and water benefits. The buffer strip subsidy is also a function of the interest rate, and the subsidy decreases with increasing interest rate.

3.2. Dairy production model

The combined milk and crop production model, developed in Study II, is presented as a simultaneous optimization problem. The aim is to maximize social welfare W (3a) in the presence of GHG emissions and nutrient runoff or maximize private profits Π (3b). The model framework consists of profits from milk production and silage and cereal cultivation subtracted by the climate and water damages resulting from these activities. The model also entails two constraints to ensure silage intake and manure applied to fields do not exceed the produced amounts (3c).

(3a) $$W = (\Omega - d^c E)H + \pi^s + \pi^c - d^c(h^s + h^c) - d^w(z^s + z^c),$$

(3b) $$\Pi = \Omega H + \pi^s + \pi^c,$$

(3c) $$s.t. \begin{cases} f^s - sH \geq 0 \\ wH - mA \geq 0. \end{cases}$$

Ω denotes the net profits per animal, H is the number of productive animals (dairy cows), and π^s and π^c denote the net profits from silage and cereal cultivation, respectively. h^s and h^c denote GHG emissions, and z^s and z^c denote nutrient runoff from silage and cereal cultivation, respectively. These environmental loads are valued by d^c, the social marginal damage from GHG emissions, and by d^w, the social marginal damage from nutrient loading. In the constraints, f^s indicates silage cultivation, s indicates silage intake per cow, w is manure excretion per cow, m denotes manure applied per hectare, and A is the total cultivation area. In the complete model, fields are spatially distributed to different distances, r, from the barn.

The decision variables of the model are concentrate intake, herd size, critical radius for silage cultivation, and manure and mineral fertilization at each distance. These continuous decision variables are the most relevant from an economic perspective. Additionally, the farmer chooses between discrete technological choices related to manure storage and spreading and the number of lactation periods. The socially and privately optimal choices of the decision variables are obtained by maximizing (3a) and (3b), respectively, while accounting for the two constraints in (3c).

Policies to guide privately optimal choices of the decision variables to the social optima include 1) a uniform carbon tax, τ^G, on all GHG emissions (4a) and 2) a nitrogen tax, τ^N, on applied nutrients from mineral fertilizers and manure (4b). The optimal tax rates are solved by imposing the taxes on the private profit maximization problem in (3b):

(4a) $$\tau^G = d^c,$$

(4b) $$\tau^N(r) = d^w z_N^j.$$

While the carbon tax in (4a) is uniform and equals the social marginal damage from GHG emissions, the nitrogen tax in (4b) is based on the social marginal damage from nutrient loading and the marginal propensity for nutrient runoff, which varies between nutrient sources (manure or mineral fertilizer) and distances. Comparing the policy instruments in the crop and dairy production models, it is noted that eq. (4b) corresponds to the latter term in eq. (2a). In crop production, the nitrogen fertilizer tax is not differentiated to separate carbon and nutrient taxes, and therefore, eq. (2a) includes both the components in (4a) and (4b). Note that in eq. (2a), the climate part of the tax is not solely marginal climate damage, as is the case in eq. (4a). In eq. (2a), the tax is directed to fertilization instead of emissions, and a multiplier is therefore needed to convert the marginal change in fertilization into the marginal change in emissions. The composition of the tax is therefore the same regardless of the production line.

3.3. Cost functions

Marginal cost functions are used to compare the costs of reducing nutrient runoff or GHG emissions within and between sectors. This comparison helps to achieve cost efficiency in reducing pollutants across the economy. Cost functions in Study III are derived by maximizing private profits with an increasing constraint on either GHG emissions or nutrient runoff. The baseline, to which the resulting profits and emissions/runoff are compared, is obtained by maximizing profits without an emissions/runoff constraint. For example, farmers may have an option to reduce fertilization to achieve a reduction in nutrient runoff. With decreasing fertilization, runoff and profits decrease due to decreasing crop yields. Lower profits constitute the real private costs of implementing the measure. If nutrient runoff is the only considered pollutant, then the term in brackets in eq. (5) is zero, giving the single pollutant abatement cost, C, for measure m and pollutant i. However, if changes in GHG emissions due to reduced fertilization, i.e., the coeffect on GHG emissions, are simultaneously accounted for, then j obtains a value, and eq. (5) is used to calculate the multiple pollutant abatement cost (Eory et al. 2013, 57). If GHG emissions decrease, then the change is negative; thus, abatement costs for nutrient runoff reduction also decrease, and vice versa.

$$(5) \qquad C_i^m = \frac{private\ real\ costs_i^m + \left(change\ in\ emissions_j^m * damage\ cost_j\right)}{emissions\ reduced_i^m}$$

Study III first derives the total cost functions for various levels of emission reductions, q_i, separately for each measure. In practice, the baseline for each measure (e.g., crop rotation or catch crop) is the privately optimal fertilizer and buffer strip levels without any constraints and the emissions and profits they together with the measure induce. Then, the study imposes a gradually tightening constraint on emissions, and the privately optimal levels of nitrogen fertilization and buffer strip width are again determined. The resulting profits with the constraint are compared with the baseline profits to yield the private real cost. Finally, a function is fitted to the points consisting of the private cost and the emissions reduction. After calculating the individual cost functions, the study assigns each measure a maximum applicable area and ranges for emissions reductions per hectare. For afforestation and green fallow, a single point of profit loss and emissions reduction is obtained as opposed to a continuous function. Finally, the total costs for reducing emissions with a varying emissions constraint, E, are minimized (eq. (6)), and a curve is fitted to these points with MATLAB or Mathematica to obtain the aggregated total abatement cost function over the studied measures.

$$(6) \qquad \min \sum_{i=1}^{n} C_i(q_i) \ s.t. \sum_{i=1}^{n} q_i \geq E$$

Marginal abatement costs are obtained by differentiating the total abatement cost function (see Simon and Blume 1994, 59).

3.4. Data

In each study, the numerical analyses are performed using Finnish agricultural data (in some cases, data from other countries are modified to Finnish statistical values). Collecting data from various sources may limit the validity of the results due to a potentially low comparability of some data sources. Additionally, large uncertainties exist such as those related to soil GHG emissions. However, data that are more consistent were not available. The uncertainties are discussed and covered to some extent by performing sensitivity analyses in each study. Table 3 compiles the used yield and runoff functions and condenses the main data sources.

Table 3. Estimated yield and runoff functions and main data sources used in the thesis

Yield and runoff functions		
Nitrogen runoff	Simmelsgaard (1991; 1998)	Study I, II, III
Phosphorus runoff	Uusitalo and Jansson (2002); Saarela et al. (1995); Ekholm et al. (2005); Uusitalo and Aura (2005)	Study I, II, III
Nitrogen yield responses	Lehtonen (2001)	Study I, II, III
Milk yield	Lehtonen (2001)	Study II, III
Dairy intake	Huhtanen et al. (2008)	Study II, III
Manure excretion and nutrient content	Nennich et al. (2005)	Study II, III
Data sources		
CH_4, enteric fermentation	Statistics Finland (2016); IPCC (2006)	Study II, III
GHGs, manure management	Statistics Finland (2016); IPCC (2006)	Study II, III
GHGs, soil	Heikkinen et al. (2013); Ervola et al. (2012)	Study I, II, III
GHGs, cultivation	Ervola et al. (2012)	Study I, II, III
Buffer strip	Lal (2004); Ervola et al. (2012)	Study I, II, III
Economic data	ProAgria (2014); OSF (2014)	Study I, II, III

4. SUMMARIES OF THE STUDIES

Study I. Does Crop Rotation with Legumes Provide an Efficient Means to Reduce Nutrient Loads and GHG Emissions?

This study examines how well crop rotations with legumes reduce nutrient runoff and GHG emissions and how these rotations perform in an economic sense compared to that of cereal monocultures. Legumes are able to fix nitrogen from the air, thus requiring less mineral fertilization. Legumes also increase the yields of the crops grown after them; i.e., they have a positive precrop effect. Rotations of different crops additionally improve soil quality and resistance to pests and diseases and decrease the risks related to varying weather conditions.

The study formulates a theoretical model and studies the effects in more detail through numerical simulations with Finnish data. The studied crop rotations consist of a cereal crop (barley, wheat or oats) and a legume mixture (pea-horse bean or red clover-grass). The goal is to maximize private profits without any constraints, private profits given the boundaries of the Finnish Agri-Environmental Scheme (period 2007-2013) or social welfare in the presence of nutrient runoff and GHG emissions. The different crop rotations and private and social optima are then compared. The study also characterizes policy instruments to guide privately optimal choices to socially optimal choices and performs a sensitivity analysis with stochastic weather.

As the main findings, in comparison to cereal monocultures, crop rotations with legumes cause less nutrient runoff and GHG emissions. Crop rotations with legumes also outperform cereal monocultures in the economic sense, especially rotations with red clover-grass, assuming adequate demand for fodder. At the national level, replacing 30% of the area under cereal cultivation with rotations based on red clover-grass could reduce GHG emissions in total by 253 800 tCO_2e and nitrogen runoff by 684 t. Rotations are more resilient towards varying weather conditions, such as excessive rain, and they thereby lower the variability in profits due to stochastic weather. The optimal policy instrument comprises two parts: a tax on nitrogen fertilizer and a buffer strip subsidy.

Study II. Dairy farm management when nutrient runoff and climate emissions count

This study presents a theoretical model framework of dairy farm production combined with crop cultivation and numerical bioeconomic simulations rooted in Finnish data. A private farmer maximizes profits from milk production, and society maximizes welfare while acknowledging the marginal social damages stemming from GHG emissions and nutrient runoff. By maximizing private profits and social welfare, the study analyzes how management decisions differ between the two optima and what kind of instruments could be used to move from the private to the social optimum.

By assumption, dairy production is located at a farm center, and the farmland has an even spatial distribution around it. The choice variables in the model are herd size, diet (concentrates and silage), land allocation (silage or cereals), and fertilization (manure or mineral fertilizers). In addition, the farmer chooses the optimal combination for manure storage (open or covered) and spreading (broadcast or injection), as well as the number of lactations. Due to the high transportation cost, manure is used close to the farm center, while mineral fertilizers with minor application costs are used further away. Both fertilizer types are not used jointly, as they are assumed to be perfect substitutes in terms of nutrients for crop growth. Additionally, in comparison to cereals, silage with high transportation costs is cultivated in nearby fields. Milk and crop production are closely linked, such as through the shadow value of silage as feed. Diet affects milk production, manure excretion, manure nutrient content, and CH_4 emissions from enteric fermentation.

In the results, the private optimum involves an excessive herd size, concentrate intake, land allocation to cereals, fertilization with a too rapid shift from manure to mineral fertilization in terms of distance, and thus excessive nutrient runoff and GHG emissions relative to the social optimum. A critical radius emerges for both fertilizer and crop types, i.e., a point in the distance where it is optimal to switch between the two options. The optimal manure application rate decreases with distance for both the private and social optima. Therefore, fields fertilized with manure always have higher nutrient application rates (for both N and P) than fields fertilized with mineral fertilizers. The most effective, but very costly, measure to reduce GHG emissions is reducing animal numbers. The options for reducing nutrient runoff are more numerous. The optimal carbon tax on all GHG emissions equals the marginal social damage from emissions. Uniform nutrient taxes are functional, although spatially differentiated taxes produce relatively higher welfare. Climate policies alone provide benefits in terms of reducing nutrient runoff, and water policies alone provide benefits in terms of reducing GHG emissions; i.e., there is coherence between the two policies.

Study III. Multiple pollutant cost-efficiency: coherent water and climate policy for agriculture

This study calculates the marginal abatement cost functions for reducing nutrient runoff and GHG emissions from agriculture when changes in the other pollutant (i.e., the coeffects) are accounted for and identifies the consequences for optimal water and climate policies. Numerical simulations use Finnish data to develop marginal abatement cost curves with a bottom-up approach. Mitigation measures included in the study are crop rotations with legumes, dairy production in a mixed dairy-crop farm, fertilization, buffer strips, catch crops, tillage methods, afforestation and green fallow. All measures are implemented on both mineral and organic soils, except for crop rotations, dairy production and catch crops, which are considered on mineral soil only.

Overall, the marginal costs for reducing both nutrient runoff and GHG emissions are lower in dairy than in crop production. Additionally, the overall potential to reduce nutrient runoff and GHG emissions in dairy production is higher. Measures that reduce GHG emissions the most are reductions in herd size and measures on organic soil. For nutrient runoff, the greatest reductions stem from measures on organic soil and from changes in land allocation, overall level of fertilization and herd size in dairy production. Most measures provide cobenefits for the other pollutants not in the policy.

Accounting for multiple pollutants changes the marginal abatement costs of the focus pollutant. If the load of the other pollutant is reduced as a result of a measure targeted to mitigate the focus pollutant, then marginal abatement costs of the focus pollutant are lowered. At the same time, the optimal reduction of the focus pollutant is increased. The used social marginal damage has a strong impact on the scale of the coeffect, i.e., on the gap between single and multiple pollutant marginal abatement cost curves. Cobenefits from the other pollutant imply a higher tax or reduction level on the focus pollutant, which increases the focus pollutant's abatement level and creates more cobenefits. The additional tax component is dependent on the mitigation level and the social marginal damage of the other pollutant. Correspondingly, codamages would lower the optimal tax or reduction level, thus creating less codamage with the lower abatement level.

5. CONCLUSIONS

This thesis studies the design of socially optimal policies for climate mitigation and water protection for two agricultural production lines: crop and dairy production. For both production lines, the thesis determines the optimal input choices and marginal abatement cost functions in the absence and presence of nutrient loads and GHG emissions using welfare and profit maximization and derivation of cost functions. Policies considered include incentives for estimated emissions (GHGs) and management practices (such as fertilizer tax and buffer strip subsidy) and standards (such as a constraint on animal numbers). In crop production, crop rotation with legumes is studied in detail, while fertilization, buffer strips, catch crops, tillage methods, afforestation and green fallow are considered when deriving marginal cost functions. Dairy production includes combined milk and crop production.

The thesis contributes to the literature in many respects. Study I formulates a theoretical economic model of crop rotation with legumes and identifies both the privately and socially optimal choices in the presence of both nutrient runoff and GHG emissions. The formulated analytical economic model of legumes in crop rotations, i.e., incorporating biologically fixed N into a typical profit maximization problem and accounting for both nutrient runoff and GHG emissions, is new in the literature. Study II presents a consistent and comprehensive theoretical and numerical model for dairy production, accounting for both nutrient runoff and GHG emissions and determining the social optimum rather than focusing only on the private optimum. In contrast to earlier literature, the focus is on the use of N and GHG emissions as opposed to solely the use of P. Study III calculates the marginal abatement cost for reducing both nutrient runoff and GHG emissions from Finnish agriculture, accounts for the coeffects of the abatement measures, and discusses the implications of the coeffects on optimal policies. This kind of calculation has not been performed for Finland or for the Baltic Sea region.

As general findings from the three studies of this thesis, the measures that reduce GHG emissions the most are reductions in herd size in dairy production and measures on organic fields in crop production. To reduce nutrient loading, organic soils are important together with measures in dairy production (land allocation, overall level of fertilization and herd size). Most measures considered in the thesis provide cobenefits for other pollutants that are not in the policy focus. The relative marginal social damage used for nutrient runoff and GHG emissions defines whether climate policies only or water policies only provide relatively more cobenefits for the other.

The main focus in each of the studies is on optimal policies. The first-best policies in general would be Pigouvian taxes on GHG emissions or nutrient runoff. For diffuse loading, this is not applicable due to problems related to measuring and monitoring, but for GHG emissions, these instruments work in principle. Pricing GHG emissions with a Pigouvian tax would simply equal the tax with marginal social damage from emissions. For nutrient runoff, due to measuring, monitoring and other difficulties, the applicable tax is necessarily second-best and therefore differentiated with respect to crop, nutrient source or distance. The applied second-best policies include, among others, uniform taxes levied on animal numbers or fertilization and subsidies based on buffer strip width or transportation of manure. Based on the findings, in comparison to the first-best policies, the second-best policies are relatively effective in producing the desired policy goals. The dissertation additionally shows the importance of considering the coeffects of agricultural measures when designing policies. In the case of cobenefits, the optimal tax on the focus pollutant is relatively higher, increasing abatement and the supply of cobenefits.

There are interesting research themes for future study. The first research topic would be to determine whether climate or water policies would result in a change in the optimal production line (such as a switch from silage to oat cultivation or from milk production to barley cultivation). This issue could be studied with a microeconomic farm-level model. Second, the models used in this thesis are limited in the sense that prices are exogenously determined. Endogenously determined prices would enable determining the equilibrium prices. This could only be studied with a general equilibrium model, which was out of the scope of the thesis. An option to combine detailed farm-level modeling with endogenous prices and market-level modeling is presented in Pérez Domínguez et al. (2009). Third, soil carbon and sequestration are not considered with respect to how the amount of soil carbon could be affected. Instead, soil carbon is considered an exogenous, fixed variable. Thus, more research is needed in the natural sciences to formulate reliable relationships. In addition to the three themes mentioned, many individual measures could have been examined, such as gypsum application to reduce P runoff in certain soil types (Ekholm et al. 2012) or dairy production in organic soils.

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